SHM
Structural Health Monitoring

Structural Health Management in the NAVY

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There is a critical need for integrated system health management (ISHM) approaches to asset maintenance. Ideally, ISHM methodologies would track the system usage and the associated loads, monitor the system degradation and materials state, monitor relevant environmental parameters and their effects on system degradation, detect insipient system damage, diagnose failure mode, predict future system performance, and recommend maintenance actions. Even though there has been considerable progress in many subareas of ISHM over the past years, there is still ample room for future improvements in all technological aspects affecting ISHM. In fact, progress in ISHM has not been uniform. Some subsystems have experienced a far greater degree of development than others. For example, engine and machinery health monitoring and diagnostics, due to its criticality, has evolved at a faster pace than structural health monitoring. This article will review some of the aspects that need to be addressed in order to make structural health monitoring (SHM) of military systems a reality in the near future.

Keywords integrated condition assessment system · comprehensive automated maintenance environment-optimized · sense and response logistics · Navy communities · fatigue life expended · life cycle cost.

1 Problem Statement

DoD weapon systems, and especially Navy systems, have been designed such that their structures, if properly maintained, will not experience structural damage (defined as crack initiation) for the design life of the system. Critical to this design philosophy is a rigorous maintenance program [1]. The Navy has accordingly developed a vast maintenance organization and associated infrastructure for the sole purpose of assuring fleet readiness. This design and maintenance philosophy has served the Navy well for many years, but it is now broadly recognized as being expensive and unsustainable, especially with regard to the demands of an increasingly aging fleet. In fact, as budgets have been reduced in recent years, some aging asset classes are not being replaced by newer ones and are therefore being required to operate well beyond their original design life. This reality makes it ever more important that we explore new approaches to asset maintenance.

There are many points throughout the life cycle of our systems where the total ownership cost can be reduced (Figure 1). Better materials with improved resistance to damage are constantly

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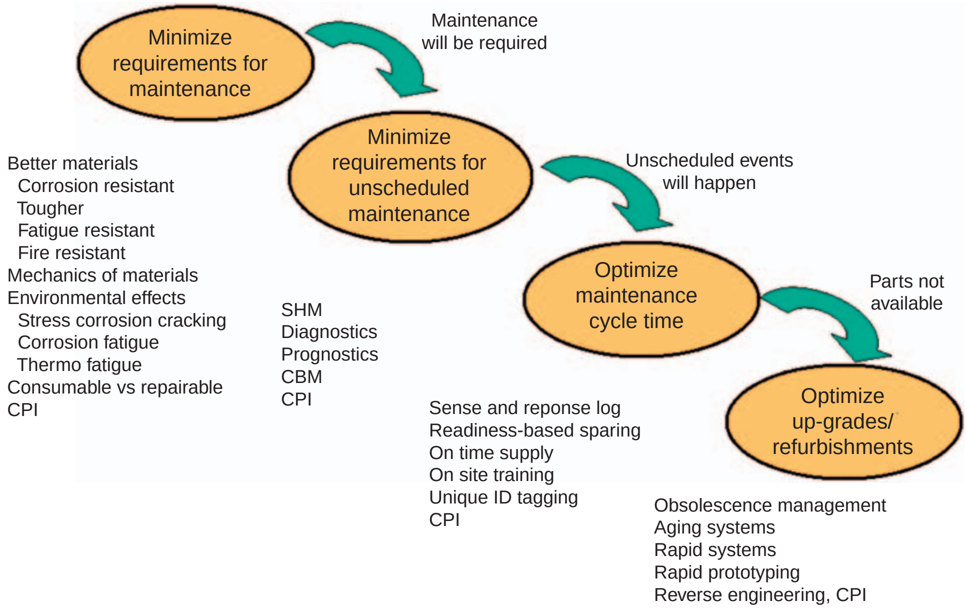

Figure 1 In reducing system LCC, health monitoring technologies can assist at many points during the useful life of the component.

being developed to minimize the requirements for scheduled and unscheduled maintenance. However, any material system will eventually degrade and maintenance will be required. In order to minimize unscheduled maintenance actions, which are the highest cost drivers and readiness degrader in any fleet, the need for monitoring all systems components for health is important. Investments in technologies such as condition based maintenance (CBM), structural health monitoring (SHM), prognostics and health management (PHM), and others are critical to both effectiveness and affordability at this juncture. But even with improved monitoring systems, damage will always happen and unscheduled maintenance will eventually be required. Therefore it is important to optimize the maintenance cycle by aligning these monitoring technologies with the logistics, operations, and maintenance communities to appropriately and effectively respond to these events. Additional savings and efficiencies can be achieved by optimizing the refurbishments and upgrades as our systems approach the end of their useful life. Despite many years of development in all these technologies, and some successful implementation of sophisticated systems aboard Navy ships and aircraft (such as the integrated condition assessment system (ICAS) [2] which is mostly centered on engine and machinery tracking, and the health and usage monitoring system (HUMS) [3] on most of many Navy helicopters and aircraft) there has been little progress in the area of SHM where the actual material state is monitored.

2 Why SHM?

A properly designed SHM system (one that in addition to monitoring loads, also monitored actual system degradation through pre-crack incubation, nucleation and growth, corrosion detection, and that also monitored relevant environmental parameters such as corrosivity, temperature, altitude, and others, and their effects on the acceleration of system degradation) could support the fleet in many ways beyond just determining the fatigue life expended (FLE) for tracked structural components. Some of these added benefits include:

- Providing a better understanding of the response of the structure under real operational conditions. This would also allow validation of the structural design throughout the entire life of the structure.

- Allowing for more streamlined structural designs (lighter weight) since the degradation of critical components would be continuously monitored during the pre-crack incubation phase, crack nucleation, and slow crack growth phase allowing for their safe removal or reconditioning well before any defect approached its critical stage.
- Enhancing confidence levels and reducing operational risk when introducing new materials, new designs, or new repair concepts into the structure [4].
- Monitoring stresses on repaired structures and the stress redistribution around patches and repairs.
- Facilitating the day-to-day management of the platform by supporting operational and maintenance decisions, especially during a surge situation where resources become limited.
- Providing knowledge of where to inspect the structure when damage develops through environmental effects or from foreign object impacts, therefore reducing inspection time and maintenance costs.
- Aiding in the decision process of life extension programs or sales to commercial companies or foreign governments.
- Providing monitoring capability for damage in hard to reach areas or inside hidden structures, therefore minimizing the need for expensive tear-down inspections.

Despite all these potential benefits of a permanently installed SHM system, the fact remains that few platforms incorporate them into their structures program. The few that do, limit their use to load monitoring in support of fatigue life tracking.

3 Obstacles to SHM

A recent paper by Derriso et al. [5] pointed out some of the reasons for such a lack of fielded SHM systems in DoD. The two main reasons were: developing a credible business case and the technological feasibility for SHM. Factors that will help create the business case include understanding the customer needs and requirements and performing a credible cost and risk analysis (reliability, maintainability, scalability, and other factors). The business case is also intimately tied to the state-of-the-art of the systems used for SHM, feasibility of technology for new capabilities needed, the type of information provided, its reliability, and the level of integration provided. This article will examine some of these factors.

3.1 Understanding Customer Requirements

There are many customers in DoD that could benefit from an SHM system. These customers belong to a number of military communities that in most cases are not collocated and in some case do not interact directly, but they all have the common goal of supporting the war fighter in an effective and efficient manner. These communities include the acquisition community; the requirements community; the operations planning community; the logistics community; the maintenance community; the design and manufacturing communities; the user community, and others. An SHM system could benefit all these communities in more ways than one. If we are to implement SHM into military systems, a credible business case needs to be articulated to as many of these communities as possible. The benefits that SHM could provide to different communities include:

- Acquisition community – by better asset life tracking and long term force planning.
- Requirements community – by having more accurate insight into the true health of existing weapon systems, and better plan for retirement of one system and the acquisition and fielding of its replacement system.
- Operations planning community – by identifying, and selecting for use, those weapon systems which require the least amount of structural maintenance activities during the period of deployment
- Logistics community – by allowing them to more accurately project out component usage rates (at an aircraft, squadron, or fleet level) and helping them to anticipate replacement rates, stocking requirements, and budget allocations. This information is of particular importance to the success of PBL contracts.
- Design and manufacturing community – because the actual response of the system to

real multi-axial loading conditions (especially from extreme loading conditions due to maneuvering, weather or combat) could be monitored and used for future system upgrades or designs. This is especially true for large platforms (ships, subs, tankers, etc.) where full article testing is not possible.

- Maintenance community – could benefit from better prognostics of upcoming structural maintenance activities for planning their workload. Being aware of developing structural issues also enables 'opportunistic' maintenance, where a maintainer could investigate or repair a detected condition when already working in that section of the aircraft for other purposes, reducing redundant efforts to gain access to certain areas and increasing maintainer efficiency.
- User community – from increased system availability due to more proactive maintenance and lower frequency of unexpected structural issues which may cause a mission abort, or simply make a system nonmission-capable and unable to begin the mission in the first place.

As an example of an integrated system for asset maintenance, the Navy has implemented the integrated condition assessment system (ICAS) on more than 100 ships [2]. ICAS gathers and processes real-time equipment data from system interfaces and machinery sensors and periodic data from hand held devices (i.e., palm pilots), for evaluating the operational condition of monitored equipment. ICAS functionality provides the benefits of time saved over manually collecting and analyzing data, of unplanned failure avoidance to reduce the occurrence of catastrophic failures and potential secondary equipment damage, of reducing unnecessary 'open and inspect' and time-directed repairs, and of providing data for failure analysis, expert system alerts, remote assistance for deployed ships as well as feedback data for RCM analysis. A typical US Navy ICAS installation consists of four to five workstations, one in each major machinery compartment as depicted in Figure 2, connected by an active local area network (LAN). Each workstation accommodates a unique configuration data set (CDS), which contains the engineering information. The main components of ICAS include:

- CDS – A core piece of ICAS is the CDS. Each workstation accommodates a unique CDS to identify tolerant and out of tolerant ranges for monitored equipment. The raw data is trended and provides plant status information that is useful to the operator/maintainer. ICAS also contains links to digital logistic products such as the engineering operational sequencing system (EOSS), planned maintenance system, and integrated electronic technical.
- Manuals – These integrated electronic technical manuals (IETMs) allow for maintenance recommendations to be linked automatically and directly to the appropriate section or card as well as browsing the entire library.
- Maintenance engineering library server (MELS) – Maintenance engineering library server is a common shore side data repository of ICAS data/information where statistical analysis can be accomplished to further maintenance savings and to gain a better knowledge of equipment operation in a marine environment.
- Integrated performance analysis report (IPAR) – Integrated performance analysis report is a generated performance analysis report that represents the health of monitored shipboard systems for a particular ship.
- Enterprise performance analysis report (ePAR) – Enterprise performance analysis report is a fleet-wide analysis report for a particular system across all ship classes.

ICAS coupled with distance support (DS 2.0) enables remote monitoring (RM). In short we are gathering shipboard data, transmitting from ship-to-shore, generating health assessment reports (IPARs) and disseminating that information to maintenance brokers and decision makers, such as regional maintenance centers (RMCs), port engineers, CLASSRONs, and the recently created surface ship life cycle management activity (SSLCM).

Another system being developed and implemented by the Navy is the comprehensive automated maintenance environment – optimized (CAMEO) system (Figure 3) which is an adaptable, open source set of automated logistics

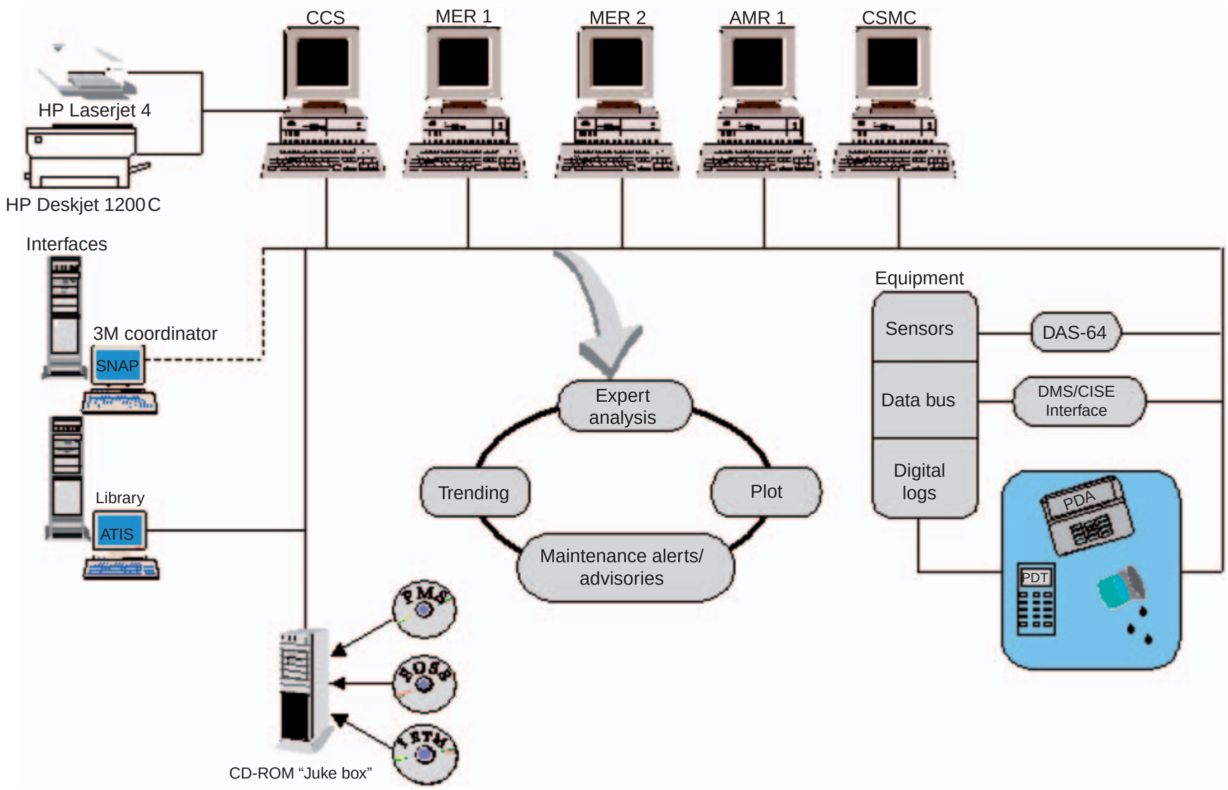

Figure 2 Typical ICAS installation aboard Navy ships. Each room with an engine (mechanical engineering room (MER), auxiliary mechanical room (AMR)) has an ICAS workstation as well as the control center (CCS).

environment (ALE) capabilities that support continuous integration and automation of operational, maintenance, and logistical processes to improve aircraft readiness and significantly decrease sustainment costs for the war fighter community [6]. Primary integrated capabilities currently available or in development include:

- A Type II/Class IV integrated electronic technical manual (IETM) providing maintenance and troubleshooting procedures, illustrated parts breakdown (IPB), electronic wiring suite (EWS), and a number of labor savings capabilities from integration with the rest of the ALE. The current IETM is not S1000D based, but an S1000D version of the IETM is in development.
- Ground station capabilities to provide conduit for post flight download and viewing/analysis of aircraft usage data, aircrew debrief, generation of needed work orders, and automated transmission of data to/from other information systems.
- Integrated usage based fatigue tracking (SAFE/FLE) for airframes and life limited dynamic components, providing greatly extended fatigue lives and significant cost avoidance in replacement parts over the life of the program.
- Electronic PMIC/parts life viewer which is a dynamically updated view of all upcoming maintenance actions on a given aircraft. This allows the user to visualize upcoming requirements when some of the maintenance requirements have changed from a fixed time interval to variable usage based actions. This same tool facilitates the inclusion of and planning for other CBM+ or SHM health indicators upon which the maintainer may need to take action.
- Automated statistical data mining is also in development to facilitate detection of meaningful trends in recorded data, either on an individual aircraft basis over time or by comparing individual aircraft to others in the fleet. This provides the 'trigger' for engineers to investigate data of interest and facilitate identification and

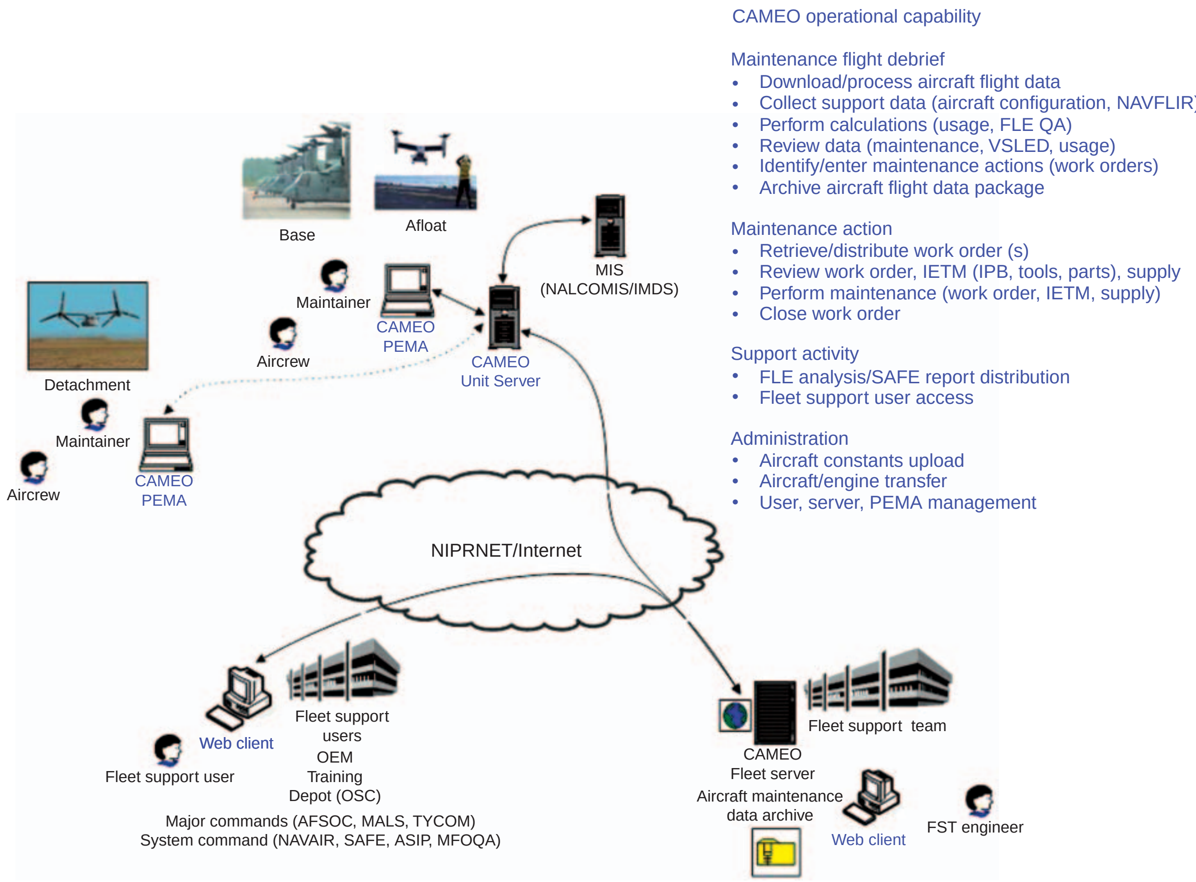

Figure 3 CAMEO architecture.

association of trends with known component failures or detected anomalies. Once a positive correlation is identified, the specific trend or combination of trends can be incorporated as a health indicator for display to the operational user in future situations.

Finally, the sense and respond logistics (S&RL) program is a 5-year effort sponsored by the Office of Naval Research enabling Logistics Modernization for the United State Marine Corps. S&RL will invest in science and technology (S&T) that will automate the detection and the consumption of logistics resources of a marine expeditionary brigade (MEB) ashore in combat operations. S&RL will also provide automation for logistics planning and assessment, supporting the cognitive processes of the logistics planner. Key concepts of this logistics transformation are operations from the Sea Base (vice the iron mountain ashore) and support of USMC enhanced company operations. The overarching S&RL system components are; a dynamic and real time networked situational awareness and knowledge creation system for assets ashore, an information architecture that will dynamically acquire, parse, process, store, distribute, create knowledge, transmit and present information in a shared data environment, and predictive and adaptive logistics decision support and planning tools to be used to generate courses of support (CoS) and courses of action (CoA).

The S&RL program will also develop a platform interface prognostic framework that will collect, interpret, and coordinate health data from USMC ground vehicles, to evaluate mission readiness, recognize trends of equipment degradation, and predict probabilities of remaining useful life for vehicle subsystems. The prognostics embedded health management capability helps fulfill the

'objective' requirement to further localize the fault/failure down to the subsystem or component levels. In addition to identifying impending failures the system must be capable of estimating the platform's capability to perform the next mission. The prognostics embedded health management capability enables the processing traditionally done centrally in a shared data environment to be distributed to the platform level. This approach dramatically reduces bandwidth required for frequent data transmission without sacrificing the ultimate fidelity of the shared data environment. Situational awareness at every level of the hierarchy is improved by removing dependence on an upstream analysis.

3.2 Cost Analysis

In addition to understanding the customer needs and requirement, it is important to provide a credible cost/benefit analysis that can be used to decide if it is worth investing in the new technology. Superficially, at least in the case of the Navy, it might appear to be difficult to provide a credible cost benefit justification for new SHM technologies since Naval weapon systems are designed so that their structures will not crack or corrode throughout their entire life if properly maintained and operated. Put in simple terms, Naval structures are designed so that they will not damage over their life time, therefore why monitor them? That is, there is no clear benefit, but there are clearly added costs. The key assumption is 'if properly maintained and operated'. The fact is that despite all of our design conservatism, maintenance infrastructure, and safe operational envelopes, damage in the form of cracks and corrosion does happen. Mission changes, weather effects, combat operations, overloads, design modifications, repairs, hard landings, material variability, design errors, and a multitude of other controllable and uncontrollable factors overcome our best efforts to avoid damage. Therefore, in developing the cost/benefit analysis it is important to document as accurately as possible the actual inspection hours and cost, maintenance hours, repair intervals, mission and readiness impact history, number of defects and defect types. This will provide a solid baseline to compare with new technology in terms of cost and operational benefits.

In determining the cost of the new technology one has to include not only the actual cost of the separate components, but also the more intangible costs such as the sensor placement studies, surface preparation, installation costs, cost of training personnel to operate and maintain system, repair cost, sensor removal, and cost of disposal at the end of life. In order for the adoption of SHM to be justified, the sum of these costs should be small and/or the benefits should be substantial. Sensors should have low cost with minimal or no maintenance requirements over the life of the platform, with high reliability and no false calls. Probably the toughest challenge is demonstrating reliability of the SHM system so that the system itself does not become a maintenance driver and reducer of weapon system availability.

3.3 Technology Maturity

Ultimately what defines SHM technology maturity is its reliability in terms of both, the hardware used and the information provided in the appropriate operational environment. In general, the hardware needs to be robust, durable, light weight, with small footprint, and with minimum power and wiring requirements. With respect to the reliability of the information provided by the SHM system, reliability needs to be quantified in terms of the probability with which a given SHM system will detect a pre-specified defect with a given confidence level. It is very difficult to specify the level of maturity of SHM technology in general terms because it depends on many factors such as the SHM modality being used (see Table 1), on the sensors and transducers used, on the type of defect being sought, and its location relative to the sensor nodes, on the structural materials being monitored, on the environmental condition and on the required metrics for success. For example, below are a few parameters that could render a mature technology immature:

- The parameters being monitored could be of a global nature (velocity, altitude, acceleration, outside temperature, and humidity) or a local nature (stress at key structural points, corrosivity at specific location);

Table 1 SHM modality options. In general, an optimal SHM modality will lie somewhere in between the two columns shown in this table.

Mechanical modeling	Physical sensors
Global monitoring	Local monitoring
Known damage site	Unknown damage location
Passive sensors	Active monitoring
Long term monitoring (cradle-to-grave)	Short term monitoring
Battery operated	Energy harvesting
Off-board data management	On-board data management
Model based analysis	Model independent methodologies
Wired sensors	Wireless sensors
Fixed sensor network	Scalable architecture
Permanently installed	Removable sensors
Mechanically fastened	Adhesively mounted
Continuous monitoring	Intermittent monitoring
Data centrally stored	Data stored locally
Sensors inside the structure	Outside the structure
Repairable sensors	Redundant sensors
Static (quasistatic) signals	Dynamic signal monitoring
Surface Mounted	Embedded

- The phenomena being monitored could be of a static nature (such as cracks and corrosion) or dynamic (such as impact event, wave slamming, flutter, acoustic emission);
- Damage locations could be known (from historical trends, components critical loading path) or unknown (corrosion, paint degradation, cracking);
- Damages could be surface breaking (surface cracks, paint discoloration) or subsurface and hidden from view (second layer cracks, hidden corrosion);
- Interrogation methods could be active (acousto-ultrasonic, eddy current) or passive (AE monitoring, environmental excitation);
- Sensors used could be wired or wireless.

Other factors that will affect the level of maturity of a specific SHM modality are listed in Table 1.

The only broad SHM technology maturity statement that can be expressed is that the SHM modalities shown on the left column of Table 1 are (for the most part) more mature than those on the right column. Therefore an SHM system that sought to perform global monitoring of static or quasistatic parameters, looking for surface breaking damage in known locations, and that use active interrogation methods with wired sensors would have far more mature technologies available than for instance an SHM system that passively sought dynamic signatures from hidden point sources of unknown origin using wireless technology. Unfortunately, it is the later system, the one that would be more desirable since cracks have a habit of appearing when least expected, hidden from view or in unexpected locations and we cannot afford to instrument the entire platform with sensors.

4 Summary

The Navy, for the most part, manages the health of its structures by using safe life principles. Structures and components are retired well before cracks initiate (defined as a 10 mil crack) as determined from full scale or component fatigue test. Large factors of safety are introduced to account for material property variability, environmental variability, and assumptions made in the analytical models used to estimate time to crack initiation. The Navy uses the FLE as the main parameter to determine asset retirement time. This requires real-time tracking of the loads experienced by the structure, which the Navy accomplishes by using a few sensors (accelerometers, strain gauges) and parametric data combined with sophisticated global models of the mechanical response of the structure. This approach has served the Navy

well as demonstrated by low historical failure rate values.

Despite the success of the current safe life methodology, it is recognized that advanced sensor technology could someday change the way we design our structures, the way we maintain them and operate them. Before this can happen, candidate technologies need to be proven robust, durable, economical and reliable while lowering overall life cycle costs (LCC). This article identified some of the Naval communities that could benefit from such advance sensor technology. The article also addressed elements of a cost analysis and technology readiness. Finally, three existing health monitoring systems, which could benefit from further enhancement with additional SHM technologies, were presented.

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